Nucleon form factors in large-volume lattice QCD at the physical point : Towards the continuum limit

Ryutaro Tsuji

Department of Physics, Graduate School of Science, Tohoku University

Abstract

In the standard model of the particle physics, the proton and neutron, in short nucleon, which are the building blocks of nuclei, are composite particles of quarks and gluons, and the interaction among them are formulated by the Quantum Chromodynamics (QCD). This indicates that the structure of nucleon is itself a nontrivial consequence of quark-gluon dynamics. QCD has a specific feature of *asymptotic freedom*, where the coupling becomes stronger in the lower energy region. Because of this property, the analytic calculations based on the perturbation theory cannot be applied in the lower energy region where hadron mass and its internal structure are relevant. The low-energy physics of QCD can be rigorously described in discretized Euclidean space-time and numerically solved by lattice QCD with High Performance Computing (HPC). Lattice QCD is the only ab initio method for numerically computing quark-gluon dynamics, and thus lattice QCD is essential for studying the internal structure of the nucleon in terms of quark and gluon degrees of freedom.

The nucleon form factors are very good probes to investigate the nucleon structure. Although great theoretical and experimental efforts for the form factors have been devoted to improving our knowledge of the nucleon structure, there are several unsolved problems and tensions associated with the fundamental properties of nucleons, such as the proton radius puzzle and the high-precision determination of the neutrino-nucleon scattering. Hence the lattice QCD is employed in this study.

In this thesis, we present results for the nucleon form factors: electric (G_E), magnetic (G_M), axial (F_A), induced pseudoscalar (F_P) and pseudoscalar (G_P) form factors, using the second PACS10 ensemble that is one of three sets of $2 + 1$ flavor lattice QCD configurations at physical quark masses in large spatial volumes (exceeding (10 fm)^3). The second PACS10 gauge configurations are generated by the PACS Collaboration with the six stout-smeared $O(a)$ improved Wilson quark action and Iwasaki gauge action at the second lattice spacing of $a = 0.063$ fm. Figure 1 shows the obtained isovector electric, magnetic and axial radii and magnetic moment from the corresponding form factors, as well as the axial-vector coupling g_A. Combining our previous results for the coarser lattice spacing [E. Shintani *et al.*, Phys. Rev. D**99,** 014510 (2019); Phys. Rev. D**102,** 019902 (2020) (erratum)], the finite lattice spacing effects on the isovector radii, magnetic moment and axial-vector coupling are investigated by comparing the two results. It was found that the effect on g_A is kept

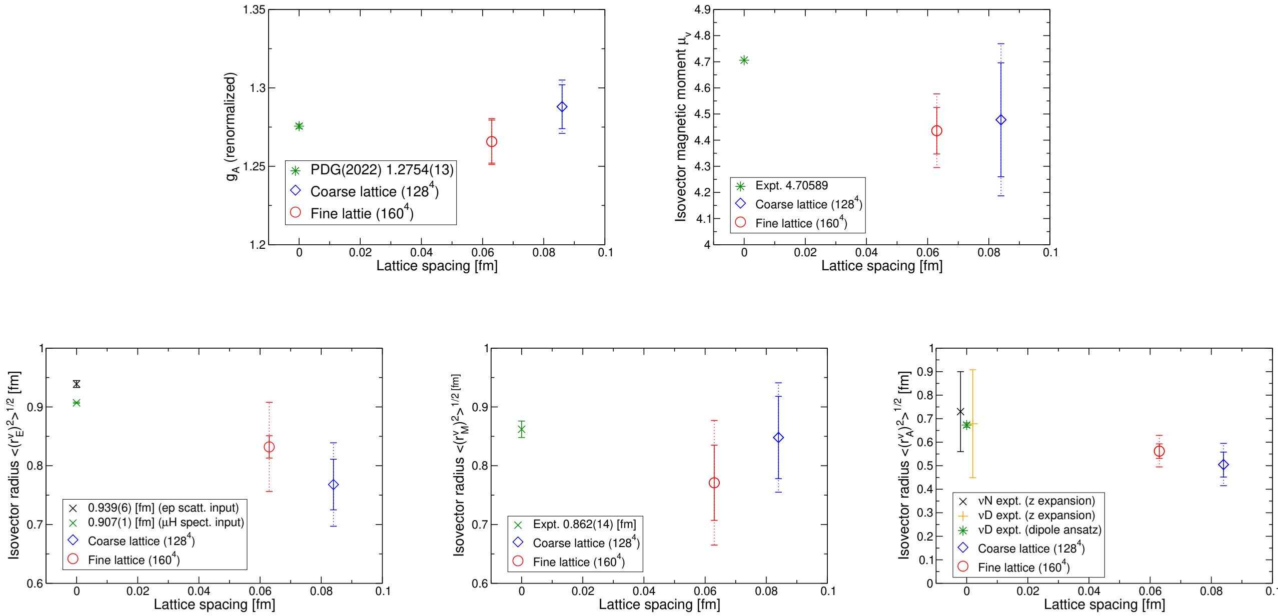

FIG. 1. Summary for our best estimates and the experimental values of the axial-vector coupling (top, left), isovector magnetic moment (top, right) and three kind of the isovector RMS radius: electric (bottom, left), magnetic (bottom, center) and axial (bottom, right). The inner error bars show the statistical error, while the outer error bars evaluated by both the statistical and systematic errors added in quadrature. Uncertainties from the excited-state contamination and the violation of the dispersion relation are taken into account as the systematic errors.

smaller than the statistical error of 2% while the effect on the isovector radius was observed as a possible discretization error of about 10%, regardless of the channel. We carefully examine the partially conserved axial vector current (PCAC) relation using a set of nucleon three-point correlation functions in order to examine the effect by $O(a)$-improvement of the axial-vector current. In addition, a feasibility study towards the continuum limit is also discussed.

References/Publication list

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